Part III

FEEDBACK

Series - shunt

1

Summary

Voltage Amplifier

خطوات
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gain

وكذلك
Rif
Routf

A summary of the rules for finding the A circuit and β for a given series–shunt feedback amplifier of the form in Fig. 8.10(a) is given in Fig. 8.11. As for using the feedback formulas in Eqs. (8.10) and (8.12) to determine the input and output resistances, it is important to note that:

1. R_i and R_o are the input and output resistances, respectively, of the A circuit in Fig. 8.11(a).
2. R_{if} and R_{of} are the input and output resistances, respectively, of the feedback amplifier, *including* R_s and R_L [see Fig. 8.10(a)].
3. The actual input and output resistances of the feedback amplifier usually exclude R_s and R_L. These are denoted R_{in} and R_{out} in Fig. 8.10(a) and can be easily determined as

$$R_{in} = R_{if} - R_s$$

$$R_{out} = 1 \Big/ \left(\frac{1}{R_{of}} - \frac{1}{R_L} \right)$$

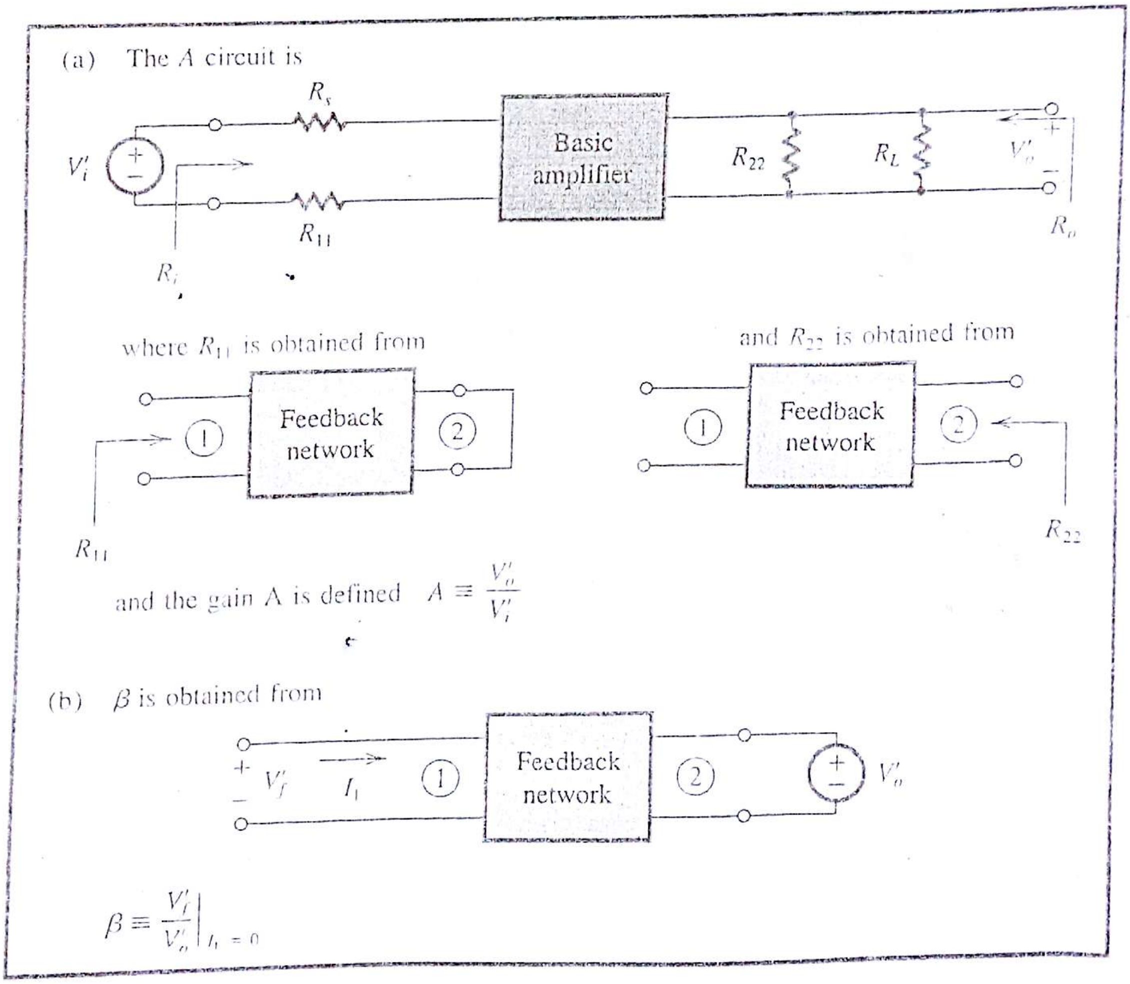

Fig. 8.11 Summary of the rules for finding the A circuit and β for the voltage-sampling series-mixing case of Fig. 8.10(a).

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EXAMPLE 8.1

Figure 8.12(a) shows an op amp connected in the noninverting configuration. The op amp has an open-loop gain μ, a differential input resistance R_{id}, and an output resistance r_o. Recall that in our analysis of op-amp circuits in Chapter 2, we neglected the effects of R_{id} (assumed it to be infinite) and of r_o (assumed it to be zero). Here we wish to use the feedback method to analyze the circuit taking both R_{id} and r_o into account. Find expressions for A, β, the closed-loop gain V_o/V_s, the input resistance R_{in} (see Fig. 8.12a), and the output resistance R_{out}. Also find numerical values, given $\mu = 10^4$, $R_{id} = 100\ \text{k}\Omega$, $r_o = 1\ \text{k}\Omega$, $R_L = 2\ \text{k}\Omega$, $R_1 = 1\ \text{k}\Omega$, $R_2 = 1\ \text{M}\Omega$, and $R_s = 10\ \text{k}\Omega$.

SOLUTION

We observe that the feedback network consists of R_2 and R_1. This network samples the output voltage V_o and provides a voltage signal (across R_1) that is mixed in series with the input source V_s.

The A circuit can be easily obtained following the rules of Fig. 8.11, and is shown in Fig. 8.12(b). For this circuit we can write by inspection

$$A \equiv \frac{V_o'}{V_i'} = \mu \frac{[R_L // (R_1 + R_2)]}{[R_L // (R_1 + R_2)] + r_o} \frac{R_{id}}{R_{id} + R_s + (R_1 // R_2)}$$

For the values given, we find that $A \simeq 6000$ V/V.

The circuit for obtaining β is shown in Fig. 8.12(c), from which we obtain

$$\beta \equiv \frac{V_f'}{V_o'} = \frac{R_1}{R_1 + R_2} \simeq 10^{-3}\ \text{V/V}$$

The voltage gain with feedback is now obtained as

$$A_f \equiv \frac{V_o}{V_s} = \frac{A}{1 + A\beta} = \frac{6000}{7} = 857\ \text{V/V}$$

The input resistance R_{if} determined by the feedback equations is the resistance seen by the external source (see Fig. 8.12a), and is given by

$$R_{if} = R_i(1 + A\beta)$$

where R_i is the input resistance of the A circuit in Fig. 8.12(b):

$$R_i = R_s + R_{id} + (R_1 // R_2)$$

For the values given, $R_i \simeq 111\ \text{k}\Omega$, resulting in

$$R_{if} = 111 \times 7 = 777\ \text{k}\Omega$$

This, however, is not the resistance asked for. What is required is R_{in}, indicated in Fig. 8.12(a). To obtain R_{in} we subtract R_s from R_{if}:

$$R_{in} = R_{if} - R_s$$

For the values given, $R_{in} = 739\ \text{k}\Omega$. The resistance R_{of} given by the feedback equations is

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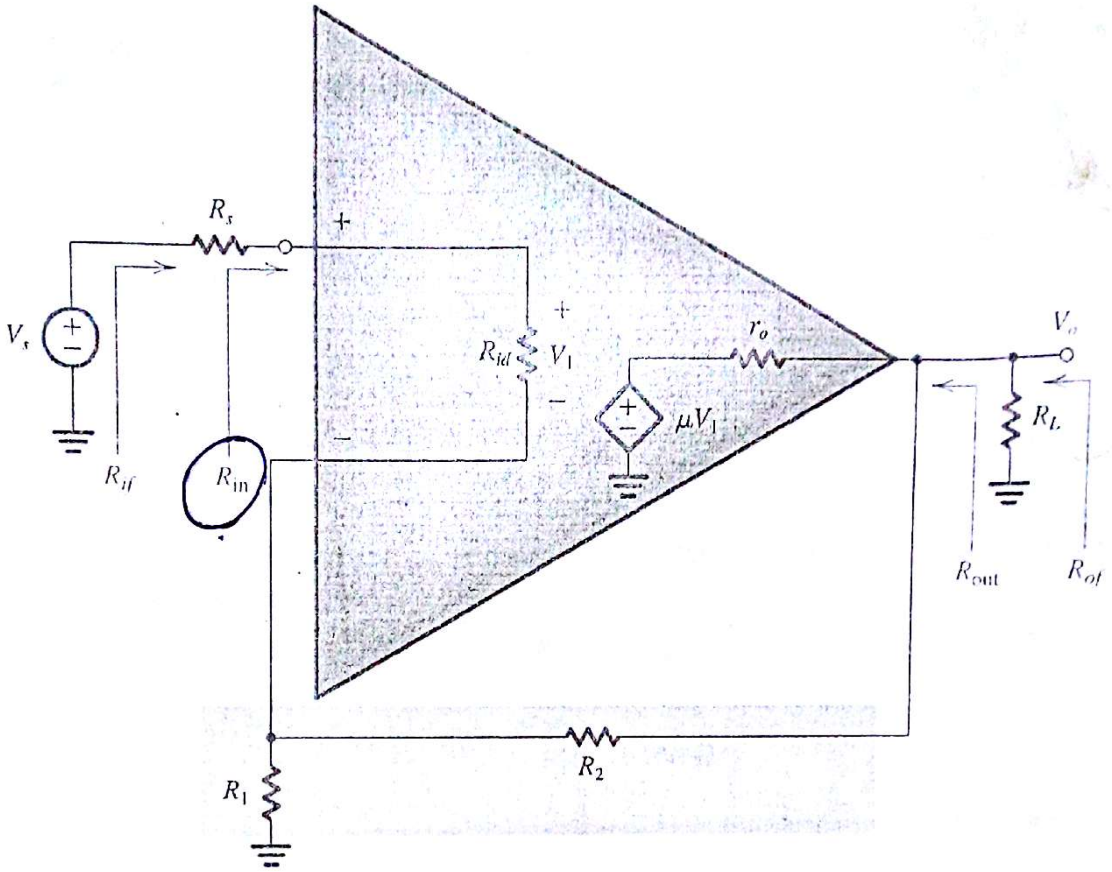
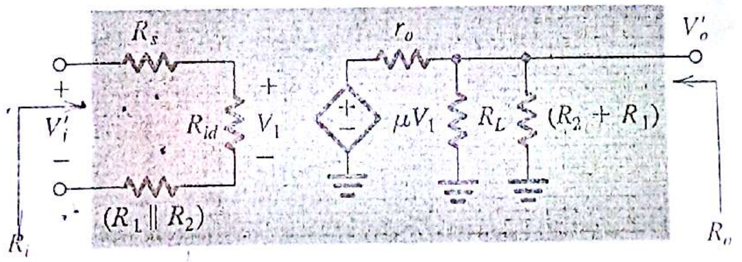
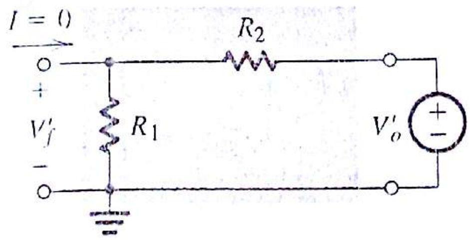


(a)



(b)



(c)

Fig. 8.12 Circuits for Example 8.1.

4

the output resistance of the feedback amplifier, including the load resistance R_L, as indicated in Fig. 8.12(a). R_{of} is given by

$$R_{of} = \frac{R_o}{1 + A\beta}$$

where R_o is the output resistance of the A circuit. R_o can be obtained by inspection of Fig. 8.12(b) as

$$R_o = r_o // R_L // (R_2 + R_1)$$

For the values given, $R_o \simeq 667\ \Omega$, and

$$R_{of} = \frac{667}{7} = 95.3\ \Omega$$

The resistance asked for, R_{out}, is the output resistance of the feedback amplifier excluding R_L. From Fig. 8.12(a) we see that

$$R_{of} = R_{\text{out}} // R_L$$

Thus

$$R_{\text{out}} \simeq 100\ \Omega$$

Exercises

8.4 If the op amp of Example 8.1 has a uniform −6-dB/octave high-frequency rolloff with $f_{3dB} = 1$ kHz, find the 3-dB frequency of the closed-loop gain V_o/V_s.

Ans. 7 kHz

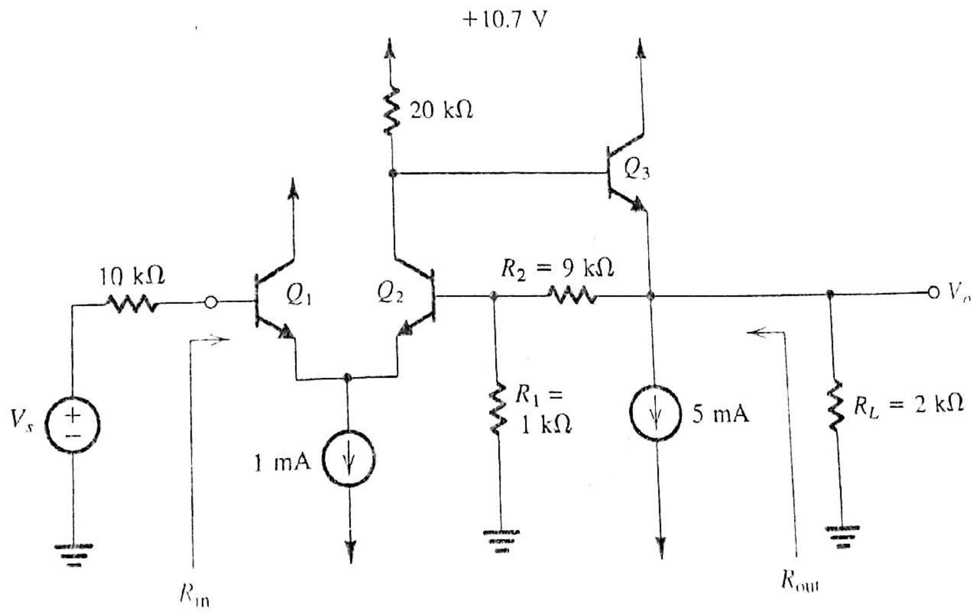


Fig. E8.5

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Series - series F.B

5

Transconductance Amplifier

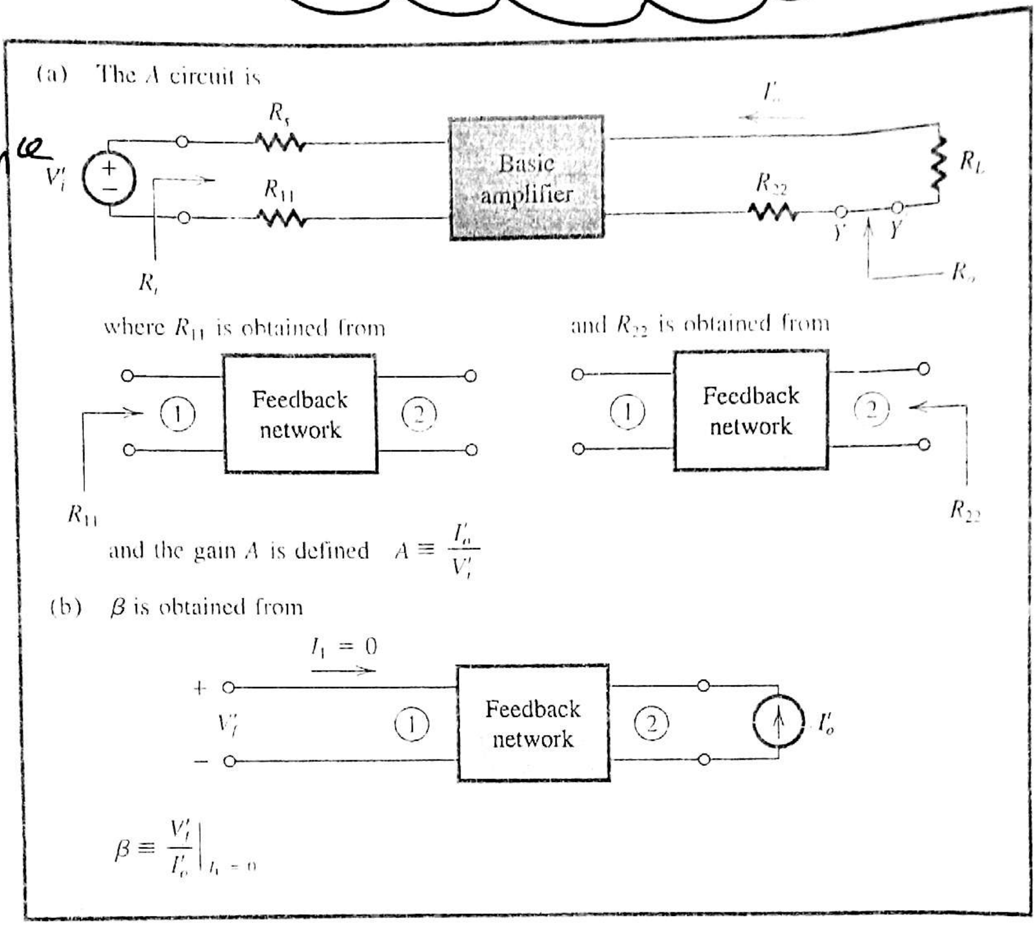

Fig. 8.16 Finding the A circuit and β for the current-sampling series-mixing (series–series) case.

Summary

For future reference we present in Fig. 8.16 a summary of the rules for finding A and β for a given series–series feedback amplifier of the type shown in Fig. 8.15(a). Note that R_i is the input resistance of the A circuit, and its output resistance is R_o, which can be determined by breaking the output loop and looking between Y and Y'. R_i and R_o can be used in Eqs. (8.16) and (8.18) to determine R_{if} and R_{of} (see Fig. 8.15b). The input and output resistances of the feedback amplifier can then be found by subtracting R_s from R_{if} and R_L from R_{of}.

$$R_{in} = R_{if} - R_s$$
$$R_{out} = R'_{of} - R_L$$

EXAMPLE 8.2

Because negative feedback extends the amplifier bandwidth, it is commonly used in the design of broadband amplifiers. One such amplifier is the MC1553. Part of the circuit of

the MC1553 is shown in Fig. 8.17(a). The circuit shown (called a *feedback triple*) is composed of three gain stages with series–series feedback provided by the network composed of R_{E1}, R_F, and R_{E2}. Assume that the bias circuit, which is not shown, causes $I_{C1} = 0.6$ mA, $I_{C2} = 1$ mA, and $I_{C3} = 4$ mA. Using these values and assuming $h_{fe} = 100$ and $r_o = \infty$, find the open-loop gain A, the feedback factor β, the closed loop gain $A_f \equiv I_o/V_s$, the voltage gain V_o/V_s, the input resistance $R_{in} = R_{if}$, and the output resistance R_{of} (between nodes Y and Y', as indicated). Now, if r_o of Q_3 is 25 kΩ, estimate an approximate value of the output resistance R_{out}.

SOLUTION

Employing the loading rules given in Fig. 8.16, we obtain the A circuit shown in Fig. 8.17(b). To find $A \equiv I_o'/V_i'$ we first determine the gain of the first stage. This can be written by inspection as

$$\frac{V_{c1}}{V_i'} = \frac{-\alpha_1(R_{C1} // r_{\pi 2})}{r_{e1} + [R_{E1} // (R_F + R_{E2})]}$$

Since Q_1 is biased at 0.6 mA, $r_{e1} = 41.7\ \Omega$. Transistor Q_2 is biased as 1 mA; thus $r_{\pi 2} = h_{fe}/g_{m2} = 100/40 = 2.5$ kΩ. Substituting these values together with $\alpha_1 = 0.99$, $R_{C1} = 9$ kΩ, $R_{E1} = 100\ \Omega$, $R_F = 640\ \Omega$, and $R_{E2} = 100\ \Omega$ results in

$$\frac{V_{c1}}{V_i'} = -14.92 \text{ V/V}$$

Next, we determine the gain of the second stage, which can be written by inspection as (note that $V_{b2} = V_{c1}$)

$$\frac{V_{c2}}{V_{c1}} = -g_{m2}\{R_{C2} // (h_{fe} + 1)[r_{e3} + (R_{E2} // (R_F + R_{E1}))]\}$$

Substituting $g_{m2} = 40$ mA/V, $R_{C2} = 5$ kΩ, $h_{fe} = 100$, $r_{e3} = 25/4 = 6.25\ \Omega$, $R_{E2} = 100\ \Omega$, $R_F = 640\ \Omega$, and $R_{E1} = 100\ \Omega$, results in

$$\frac{V_{c2}}{V_{c1}} = -131.2 \text{ V/V}$$

Finally, for the third stage we can write by inspection

$$\frac{I_o'}{V_{c2}} = \frac{I_{e3}}{V_{b3}} = \frac{1}{r_{e3} + (R_{E2} // (R_F + R_{E1}))}$$
$$= \frac{1}{6.25 + (100 // 740)} = 10.6 \text{ mA/V}$$

Combining the gains of the three stages results in

$$A \equiv \frac{I_o'}{V_i'} = -14.92 \times -131.2 \times 10.6 \times 10^{-3}$$
$$= 20.7 \text{ A/V}$$

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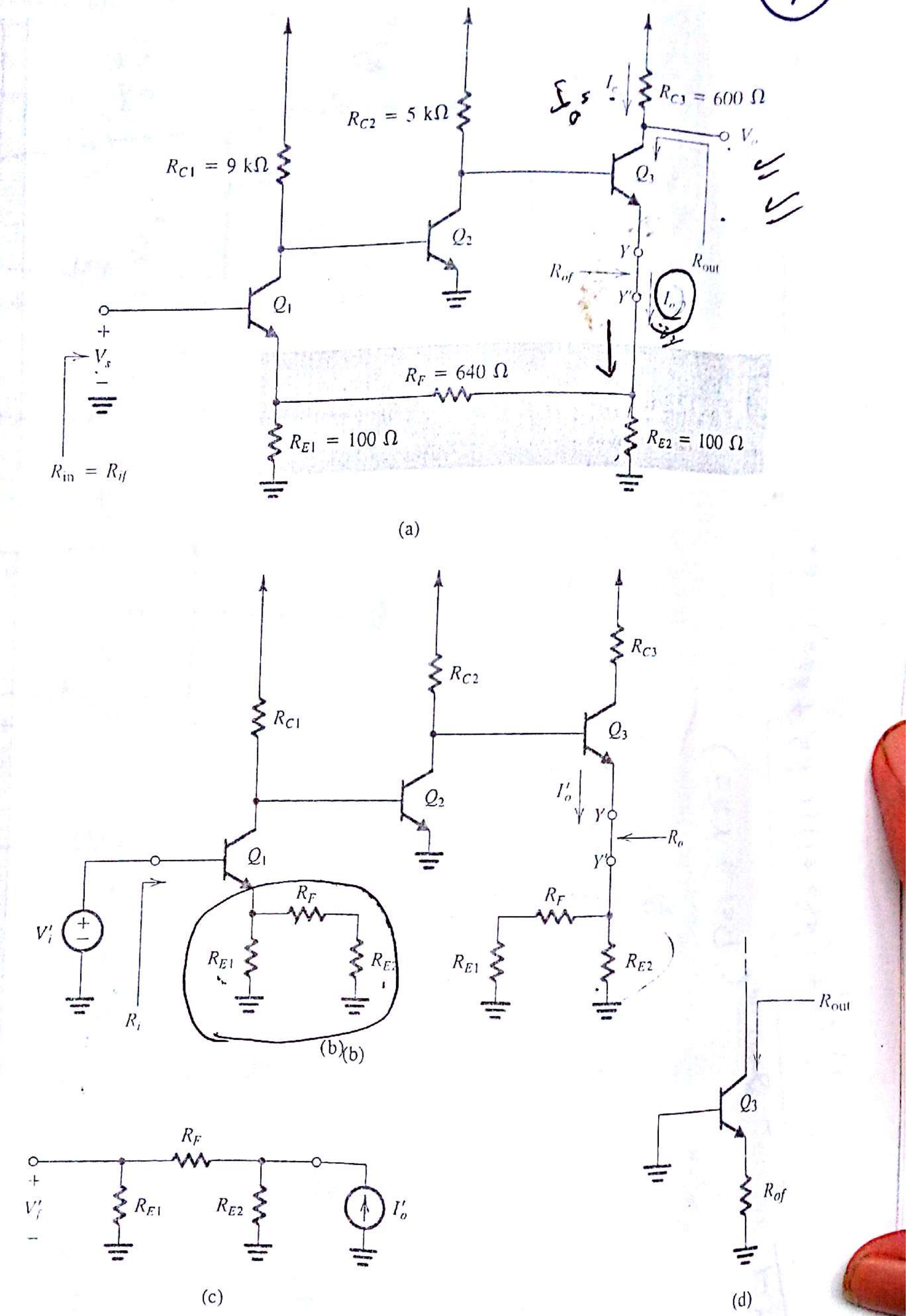

Fig. 8.17 Circuits for Example 8.2.

Model for the circuit

$h_{fe} = \beta$

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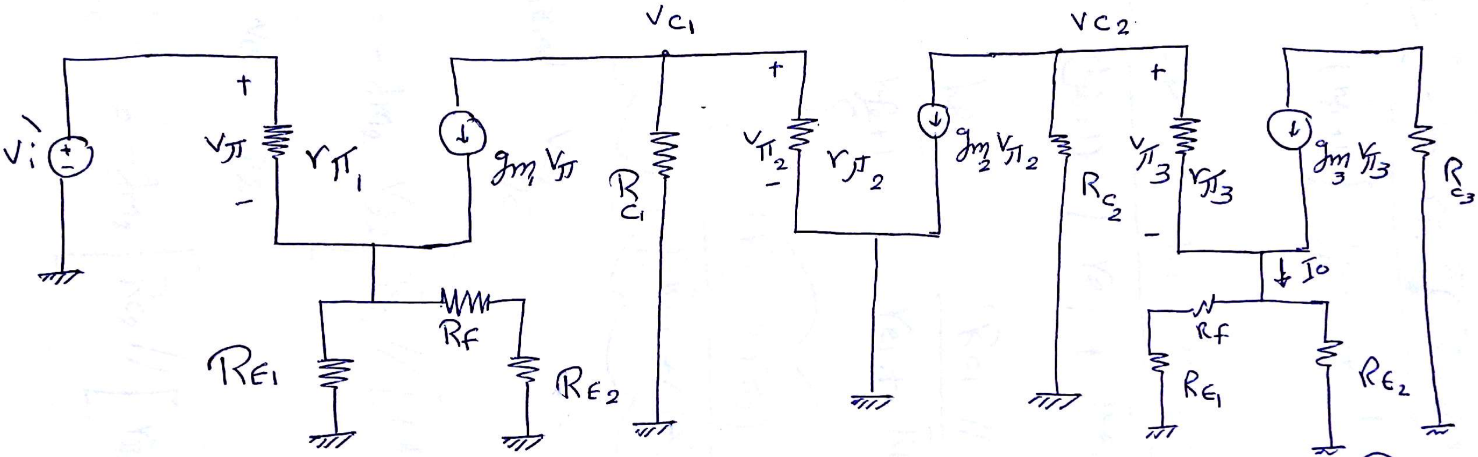


$\therefore\ V_{C1} = -g_{m1} V_{\pi_1} (R_{C1} \parallel r_{\pi 2})$

and $V_i = i_b \left(r_{\pi_1} + (h_{fe}+1)\left((R_F + R_{E2}) \parallel R_{E1} \right)\right)$

$i_b = V_\pi / r_\pi$, $h_{fe} = \beta$

$$\therefore\ \frac{V_{C1}}{V_i} = \frac{-g_{m1} (R_{C1} \parallel r_{\pi 2})}{\frac{1}{r_\pi}\left(r_{\pi_1} + (h_{fe}+1)\left((R_F + R_{E2}) \parallel R_{E1}\right)\right)} = \frac{-g_{m1} r_{\pi_1} (R_{C1} \parallel r_{\pi_2})}{r_{\pi_1} + (h_{fe}+1)\left[R_{E1} \parallel (R_F + R_{E2})\right]}$$

$r_\pi = \beta / g_m$

$r_e \cong \frac{1}{g_m} \cong \frac{\alpha}{g_m}$

$r_\pi = (\beta+1)\, r_e$

$$\therefore \frac{V_{C1}}{V_i} = \frac{-g_{m1} r_{\pi_1} (R_{C1} // r_{\pi_2})}{(h_{fe}+1)\left[\frac{r_{\pi 1}}{h_{fe}+1} + R_{E1} // (R_f + R_{E_2})\right]}$$ 9

$$= \frac{-\beta \quad R_{C_1} // r_{\pi 2}}{(h_{fe}+1) \; [r_{e_1} + R_{E1} // (R_f + R_{E_2})]}$$

$$= -\frac{h_{fe}}{h_{fe}+1} \; \frac{R_{C1} // r_{\pi_2}}{r_{e1} + R_{E1} // (R_f + R_{E_2})}$$

$$\frac{V_{C1}}{V_1} = \frac{-\alpha \quad (R_{C1} // r_{\pi 2})}{r_{e1} + [R_{E1} // (R_F + R_{E_2})]}$$

and To find $\frac{V_{C2}}{V_{C1}}$

$$V_{C2} = -g_{m_2} \; V_{\pi_2} \left[R_{C_2} // \left[r_{\pi_3} + (h_{fe}+1) (R_{E_2} // (R_f + R_{E_1}) \right] \right]$$

and $V_{C1} = V_{\pi_2}$

$$\therefore \frac{V_{C2}}{V_{C1}} = -g_{m_2} \left[R_{C_2} // \left[r_{\pi_3} + (h_{fe}+1) \left((R_f + R_{E1}) // R_{E_2} \right) \right] \right]$$

10

$$\frac{V_{c2}}{V_{c1}} = -g_{m_2}\left[R_{c2} \,//\, \left[(h_{fe}+1)\left[\frac{r_{\pi3}}{h_{fe}+1} + R_{E_2} \,//\, (R_f + R_{E_1})\right]\right]\right]$$

$$= -g_{m2}\left[R_{c_2} \,//\, (h_{fe}+1)\left[r_{e_3} + R_{E2} \,//\, (R_f + R_{E_1})\right]\right]$$

$$= \text{\_\_\_\_\_\_}$$

and $\dfrac{I_o}{V_{c2}} = \dfrac{I_{e_3}}{V_{b_3}} = \dfrac{\cancel{g_m V_{\pi3} + V_{\pi3}}}{}$

$$I_{e_3} = g_{m_3} V_{\pi3} + I_{b_3}$$

$$= g_{m_3} V_{\pi3} + I_{b_3}$$

$$\therefore \frac{I_o'}{V_{c_2}} = \frac{1}{r_{e_3} + (R_{E_2} \,//\, (R_f + R_{E_1}))}$$

and $A = \dfrac{I_o'}{V_i} = \dfrac{V_{c1}}{V_i'} * \dfrac{V_{c_2}}{V_{c_1}} * \dfrac{I_o'}{V_{c_2}}$

$$= \text{\_\_\_\_\_\_}$$

The circuit for determining the feedback factor β is shown in Fig. 8.17(c), from which we find

$$\beta \equiv \frac{V_f'}{I_o'} = \frac{R_{E2}}{R_{E2} + R_F + R_{E1}} \times R_{E1}$$

$$= \frac{100}{100 + 640 + 100} \times 100 = 11.9\ \Omega$$

The closed-loop gain A_f can now be found from

$$A_f \equiv \frac{I_o}{V_s} = \frac{A}{1 + A\beta}$$

$$= \frac{20.7}{1 + 20.7 \times 11.9} = 83.7\ \text{mA/V}$$

The voltage gain is found from

$$\frac{V_o}{V_s} = \frac{-I_c R_{C3}}{V_s} \simeq -A_f R_{C3}$$

$$= -83.7 \times 10^{-3} \times 600 = -50.2\ \text{V/V}$$

The input resistance of the feedback amplifier is given by

$$R_{if} = R_i(1 + A\beta)$$

where R_i is the input resistance of the A circuit. The value of R_i can be found from the circuit in Fig. 8.17(b) as follows:

$$R_i = (h_{fe} + 1)[r_{e1} + (R_{E1} // (R_F + R_{E2}))]$$

$$= 13.65\ \text{k}\Omega$$

Thus,

$$R_{if} = 13.65(1 + 20.5 \times 11.9) = 3.34\ \text{M}\Omega$$

To find the output resistance R_o of the A circuit in Fig. 8.17(b), we break the circuit between Y and Y'. The resistance looking between these two nodes can be found to be

$$R_o = [R_{E2} // (R_F + R_{E1})] + r_{e3} + \frac{R_{C2}}{h_{fe} + 1}$$

which, for the values given, yields $R_o = 143.9\ \Omega$. The output resistance R_{of} of the feedback amplifier can now be found as

$$R_{of} = R_o(1 + A\beta) = 143.9(1 + 20.7 \times 11.9) = 35.6\ \text{k}\Omega$$

Note that the feedback stabilizes the emitter current of Q_3, and thus the output resistance that is determined by the feedback formula is the resistance of the emitter loop (i.e., between Y and Y'), which we have just found, and not the resistance looking into the collector[2] of Q_3. This is because the output resistance r_o of Q_3 is in effect outside the feedback loop. We

[2] This important point was first brought to the authors' attention by Gordon Roberts (see Roberts and Sedra, 1992).

shunt-shunt F.B

(12)

trans-Resistance Amplifier

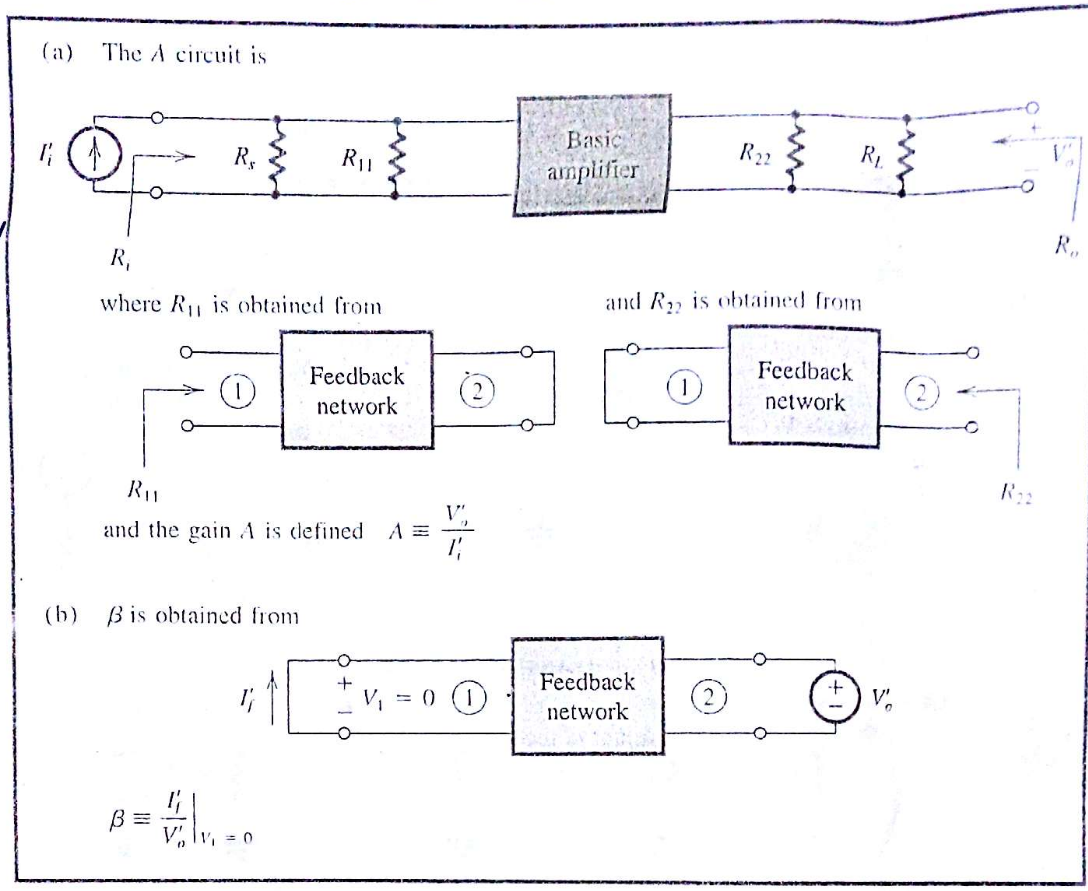


Fig. 8.20 Finding the A circuit and β for the voltage-sampling shunt-mixing (shunt–shunt) case.

(For the definition of the y parameters, refer to Appendix B.) Finally, we note that once R_{if} and R_{of} are determined using the feedback formulas (Eqs. 8.21 and 8.22), the input and output resistances of the amplifier proper (see definitions in Fig. 8.19) can be obtained as,

$$R_{\text{in}} = 1\Big/\left(\frac{1}{R_{if}} - \frac{1}{R_s}\right)$$

$$R_{\text{out}} = 1\Big/\left(\frac{1}{R_{of}} - \frac{1}{R_L}\right)$$

EXAMPLE 8.3

We want to analyze the circuit of Fig. 8.21(a) to determine the small-signal voltage gain V_o/V_s, the input resistance R_{in}, and the output resistance $R_{\text{out}} = R_{of}$. The transistor has $\beta = 100$.

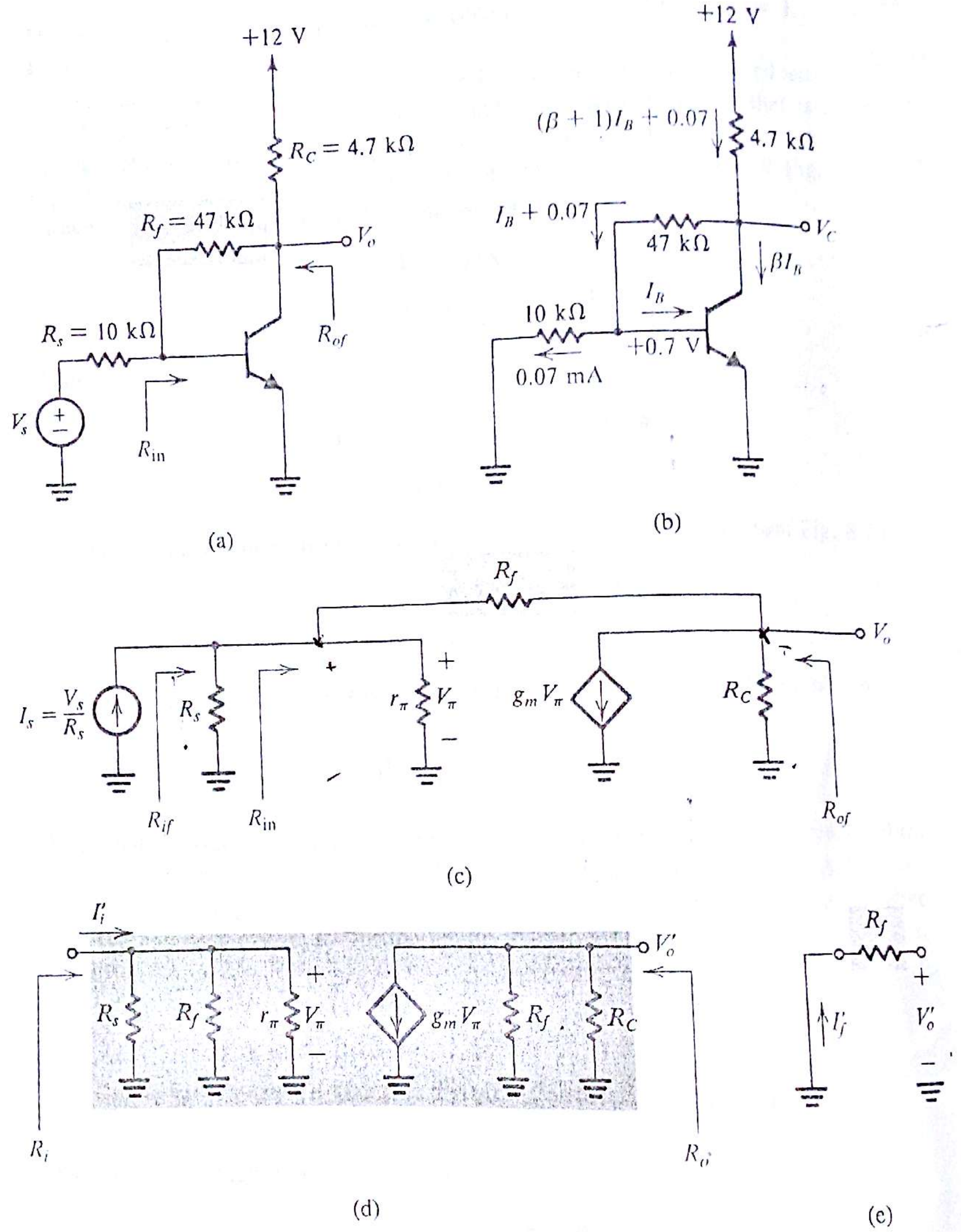


Fig. 8.21 Circuits for Example 8.3.

SOLUTION

First we determine the transistor dc operating point. The dc analysis is illustrated in Fig. 8.21(b), from which we can write

$$V_C = 0.7 + (I_B + 0.07)47 = 3.99 + 47I_B \quad \text{and} \quad \frac{12 - V_C}{4.7} = (\beta + 1)I_B + 0.07$$

(14)

These two equations can be solved to obtain $I_B \simeq 0.015$ mA, $I_C \simeq 1.5$ mA, and $V_C = 4.7$ V.

To carry out small-signal analysis we first recognize that the feedback is provided by R_f, which samples the output voltage V_o and feeds back a current that is mixed with the source current. Thus it is convenient to use the Norton source representation, as shown in Fig. 8.21(c). The A circuit can be easily obtained using the rules of Fig. 8.20, and it is shown in Fig. 8.21(d). For the A circuit we can write by inspection

$$V_\pi = I_i'(R_s//R_f//r_\pi)$$

$$V_o' = -g_m V_\pi (R_f//R_C)$$

Thus

$$A = \frac{V_o'}{I_i'} = -g_m(R_f//R_C)(R_s//R_f//r_\pi)$$
$$= -358.7 \text{ k}\Omega$$

The input and output resistances of the A circuit can be obtained from Fig. 8.21(d) as

$$R_i = R_s//R_f//r_\pi = 1.4 \text{ k}\Omega$$

$$R_o = R_C//R_f = 4.27 \text{ k}\Omega$$

The circuit for determining β is shown in Fig. 8.21(e), from which we obtain

$$\beta \equiv \frac{I_f'}{V_o'} = -\frac{1}{R_f} = -\frac{1}{47 \text{ k}\Omega}$$

Note that as usual the reference direction for I_f has been selected so that I_f subtracts from I_s. The resulting negative sign of β should cause no concern, since A is also negative, keeping the loop gain $A\beta$ positive, as it should be for the feedback to be negative.

We can now obtain A_f (for the circuit in Fig. 8.21c) as

$$A_f \equiv \frac{V_o}{I_s} = \frac{A}{1 + A\beta}$$

$$\frac{V_o}{I_s} = \frac{-358.7}{1 + 358.7/47} = \frac{-358.7}{8.63} = -41.6 \text{ k}\Omega$$

To find the voltage gain V_o/V_s we note that

$$V_s = I_s R_s$$

Thus

$$\frac{V_o}{V_s} = \frac{V_o}{I_s R_s} = \frac{-41.6}{10} \simeq -4.16 \text{ V/V}$$

The input resistance with feedback (see Fig. 8.21c) is given by

$$R_{if} = \frac{R_i}{1 + A\beta}$$

Thus

$$R_{if} = \frac{1.4}{8.63} = 162.2\ \Omega$$

This is the resistance seen by the current source I_s in Fig. 8.21(c). To obtain the input resistance of the feedback amplifier excluding R_s (that is, the required resistance R_{in}) we subtract $1/R_s$ from $1/R_{if}$ and invert the result; thus $R_{in} = 165\ \Omega$. Finally, the amplifier output resistance R_{of} is evaluated using

$$R_{of} = \frac{R_o}{1 + A\beta} = \frac{4.27}{8.63} = 495\ \Omega$$

An Important Note

The method we have been employing for the analysis of feedback amplifiers is predicated on two premises: Most of the forward transmission occurs in the basic amplifier, and most of the reverse transmission (feedback) occurs in the feedback network. For each of the three topologies considered thus far, these two assumptions were mathematically expressed as conditions on the relative magnitudes of the forward and reverse two-port parameters of the basic amplifier and the feedback network. Since the circuit considered in Example 8.3 is simple, we have a good opportunity to check the validity of these assumptions.

Reference to Fig. 8.21(d) indicates clearly that the basic amplifier is unilateral; thus *all* of the reverse transmission takes place in the feedback network. The case with forward transmission, however, is not so clear, and we must evaluate the forward y parameters. For the A circuit in Fig. 8.21(d), $y_{21} = g_m$. For the feedback network it can be easily shown that $y_{21} = -1/R_f$. Thus for our analysis method to be valid we must have $g_m \gg 1/R_f$. For the numerical values in Example 8.3, $g_m = 60$ mA/V and $1/R_f = 0.02$ mA/V, indicating that this assumption is more than justified. Nevertheless, in designing feedback amplifiers, care should be taken in choosing component values to ensure that the two basic assumptions are valid.

The Shunt–Series Configuration

Q)

Figure 8.22 shows the ideal structure of the shunt–series feedback amplifier. It is a current amplifier whose gain with feedback is defined as

$$A_f \equiv \frac{I_o}{I_s} = \frac{A}{1 + A\beta} \tag{8.23}$$

The input resistance with feedback is the resistance seen by the current source I_s and is given by

$$R_{if} = \frac{R_i}{1 + A\beta} \tag{8.24}$$

Again we note that the shunt connection at the input reduces the input resistance. The output resistance with feedback is the resistance seen by breaking the output circuit, such as between O and O′, and looking between the two terminals thus generated (that is, between O

shunt-series F.B

Current Amplifier

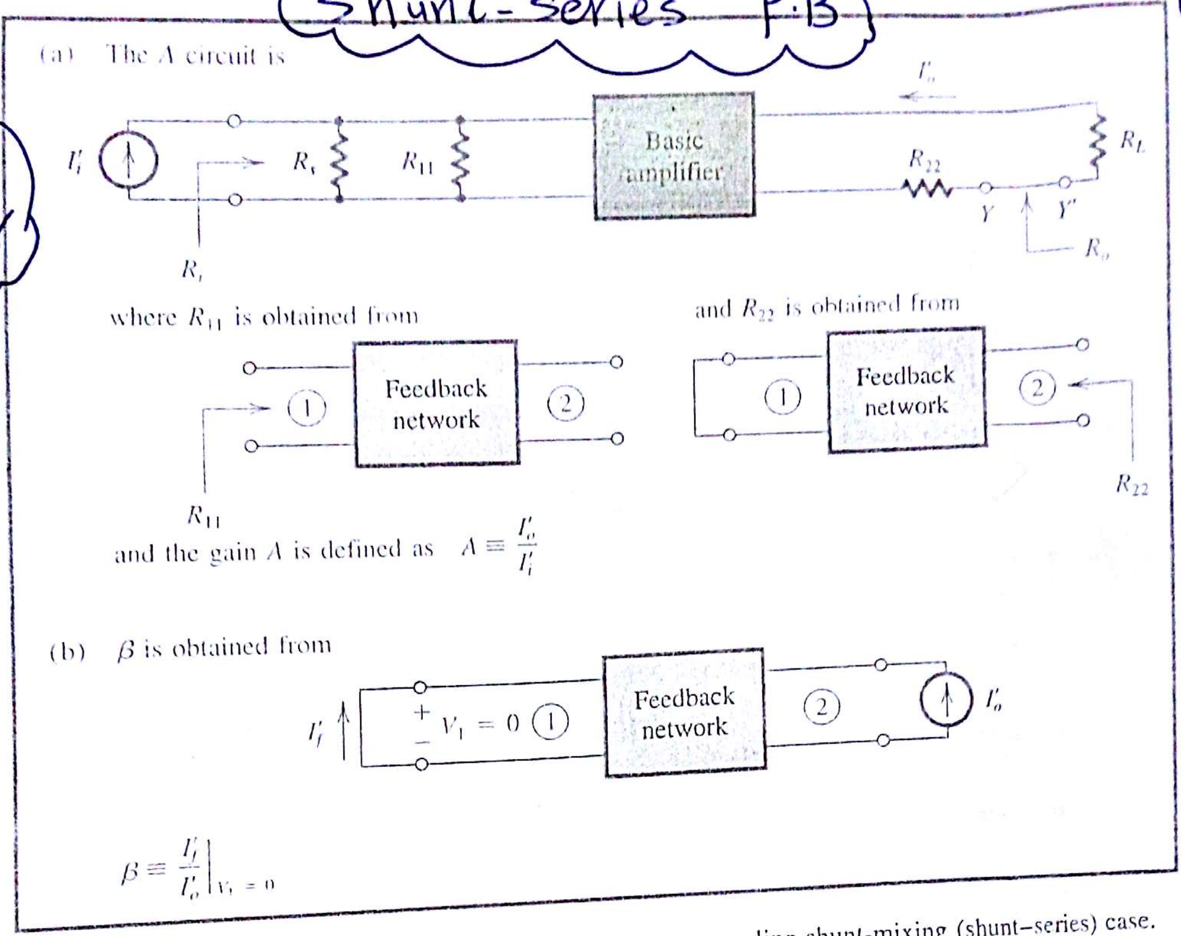


Fig. 8.24 Finding the A circuit and β for the current-sampling shunt-mixing (shunt–series) case.

(For the definition of the g parameters refer to Appendix B.) Finally, we note that once R_{if} and R_{of} have been determined using the feedback equations (Eqs. 8.24 and 8.25), the input and output resistances of the amplifier proper, R_{in} and R_{out} (Fig. 8.23), can be found as

$$R_{in} = 1\Big/\left(\frac{1}{R_{if}} - \frac{1}{R_s}\right)$$

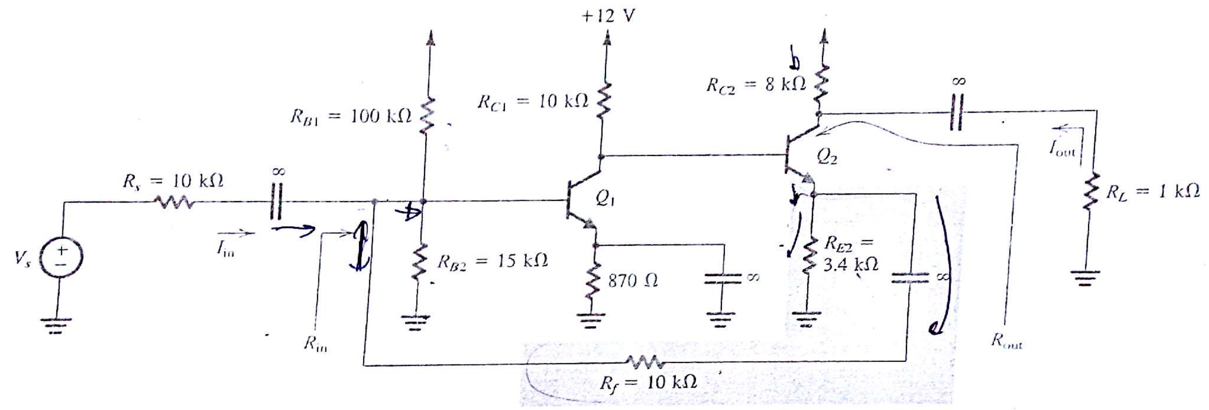
$$R_{out} = R_{of} - R_L$$

EXAMPLE 8.4

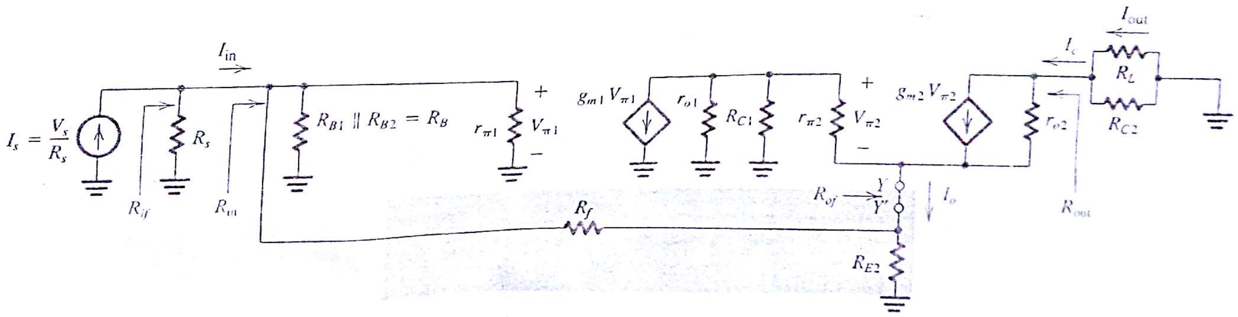
Figure 8.25 shows a feedback circuit of the shunt–series type. Find I_{out}/I_{in}, R_{in}, and R_{out}. Assume the transistors to have $\beta = 100$ and $V_A = 75$ V.

SOLUTION

We begin by determining the dc operating points. In this regard we note that the feedback signal is capacitively coupled; thus the feedback has no effect on dc bias. Neglecting the



(a)



(b)

Fig. 8.25 Circuits for Example 8.4.

17

19

effect of finite transistor β and V_A, the dc analysis proceeds as follows:

$$V_{B1} \simeq 12\frac{15}{100 + 15} = 1.57 \text{ V}$$

$$V_{E1} \simeq 1.57 - 0.7 = 0.87 \text{ V}$$

$$I_{E1} = 0.87/0.87 = 1 \text{ mA}$$

$$V_{C1} \simeq 12 - 10 \times 1 = 2 \text{ V}$$

$$V_{E2} \simeq 2 - 0.7 = 1.3 \text{ V}$$

$$I_{E2} \simeq 1.3/3.4 \simeq 0.4 \text{ mA}$$

$$V_{C2} \simeq 12 - 0.4 \times 8 = 8.8 \text{ V}$$

The amplifier equivalent circuit is shown in Fig. 8.25(b), from which we note that the feedback network is composed of R_{E2} and R_f. The feedback network samples the emitter current of Q_2, I_o, which is approximately equal to the collector current I_c. Also note that the required current gain, I_{out}/I_{in}, will be slightly different than the closed-loop current gain $A_f \equiv I_o/I_s$.

The A circuit is shown in Fig. 8.25(c), where we have obtained the loading effects of the feedback network using the rules of Fig. 8.24. For the A circuit we can write

$$V_{\pi 1} = I_i'[R_s//(R_{E2} + R_f)//R_B//r_{\pi 1}]$$

$$V_{b2} = -g_{m1}V_{\pi 1}\{r_{o1}//R_{C1}//[r_{\pi 2} + (\beta + 1)(R_{E2}//R_f)\}$$

$$I_o' \simeq \frac{V_{b2}}{r_{e2} + (R_{E2}//R_f)}$$

where we have neglected the effect of r_{o2}. These equations can be combined to obtain the open-loop current gain A,

$$A \equiv \frac{I_o'}{I_i'} \simeq -201.45 \text{ A/A}$$

The input resistance R_i is given by

$$R_i = R_s//(R_{E2} + R_f)//R_B//r_{\pi 1} = 1.535 \text{ k}\Omega$$

The output resistance R_o is that found by looking into the output loop of the A circuit between nodes Y and Y' (see Fig. 8.25c) with the input excitation I_i' set to zero. Neglecting the small effect of r_{o2} it can be shown that

$$R_o = (R_{E2}//R_f) + r_{e2} + \frac{R_{C1}//r_{o1}}{\beta + 1}$$
$$= 2.69 \text{ k}\Omega$$

The circuit for determining β is shown in Fig. 8.25(d), from which we find

$$\beta \equiv \frac{I_f'}{I_o'} = -\frac{R_{E2}}{R_{E2} + R_f} = -\frac{3.4}{13.4} = -0.254$$